Advanced Mirror Technology Development (AMTD): Year Five Status

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SPIE O&P 2017

NASA Strategic Astrophysics Technology Grant

AMTD Status

AMTD-1 completed in 2014.

AMTD-2 will complete in 2017.

- Fabricate ⅓-scale model of 4-m x 400-mm class ~150 Hz ULE® mirror

  Done in 2016 – Harris Mirror Substrate

- Qualify two candidate lightweight primary mirrors by characterizing their optical performance from 250K to ambient

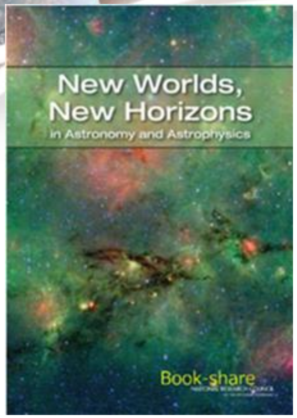
  Done in 2016 – Schott Mirror

  2017 – Harris Mirror

- Integrated Modeling Tools and Point Designs:

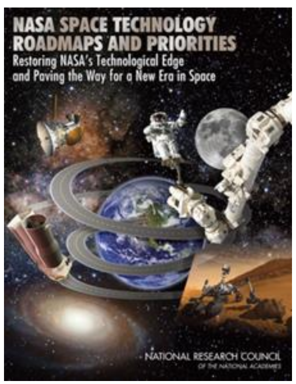
  Done in 2016 – Infused into HabEx Study

Space Telescopes require Mirror Technology



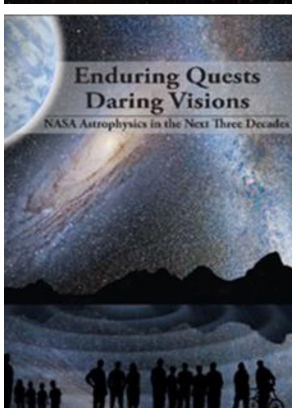
Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

- Exoplanet Mission (New-Worlds Explorer)
- UVOIR Space Telescope (4 meter or larger)



2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

- New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …



2014 Enduring Quests Daring Visions recommended:

- LUVOIR Surveyor with sensitivity to locate the bulk of planets in the solar neighborhood and reveal the details of their atmospheres.

Objective

Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.

AMTD’s objective is to mature to towards TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

Multiple Technology Paths

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

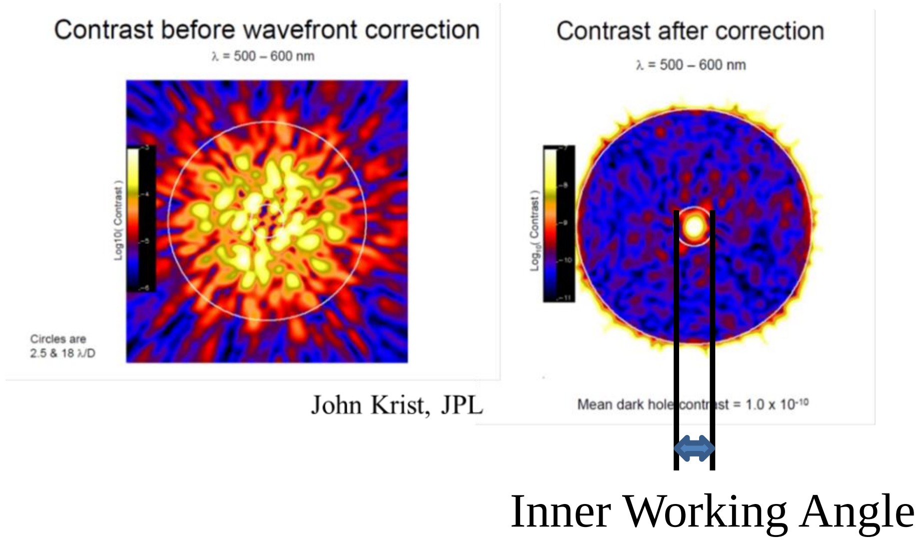
To provide the science community with options, we are pursuing multiple technology paths for both monolithic and segmented aperture telescopes.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

– Very Smooth Surfaces	< 10 nm rms
– Thermal Stability	Low CTE Material
– Mechanical Stability	High Stiffness Mirror Substrates

‘The’ System Challenge: Dark Hole

- Imaging an exoplanet, requires blocking 10^{10} of host star’s light
- An internal coronagraph (with deformable mirrors) can create a ‘dark hole’ with < 10^{-10} contrast.



John Krist, JPL

- **Ultra-smooth, Ultra-Stable Mirror Systems are critical to achieving and maintaining the ‘dark hole’**

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

Shaklan, Green and Palacios, “TPFC Optical Surface Requirements”, SPIE 626511-12, 2006.

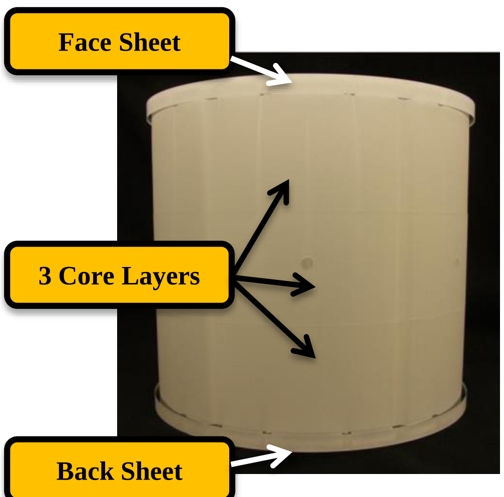
Large Stable Mirror Substrates

Phase 1 demonstrated stacked core low-temperature fusion process to cost effectively make mirrors thicker than 300 mm by making a 40 cm ‘cut-out’ of a 4-m mirror.

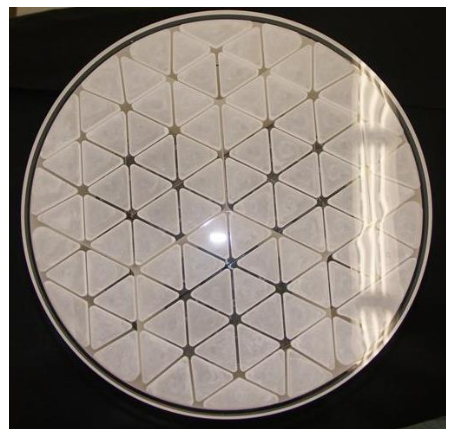
43 cm Deep Core Mirror

Harris successfully demonstrated 5-layer ‘stack & fuse’ technique which fuses 3 core structural element layers to front & back faceplates.

43 cm ‘cut-out’ of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate

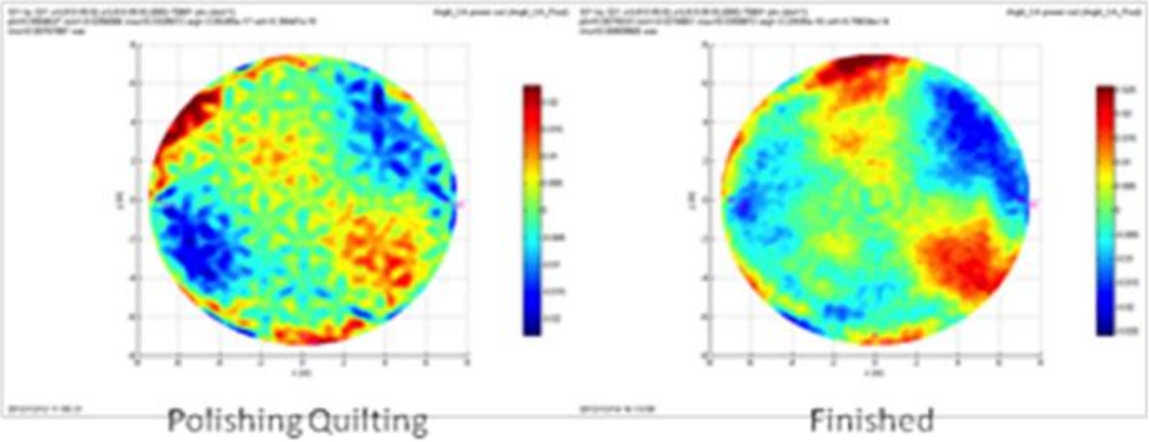
Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

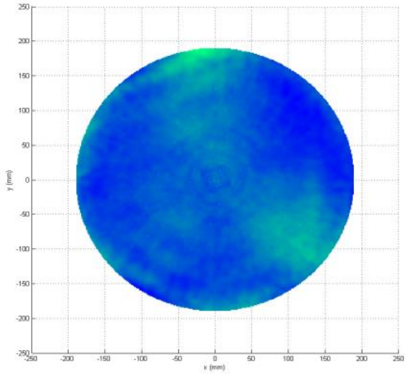
Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.

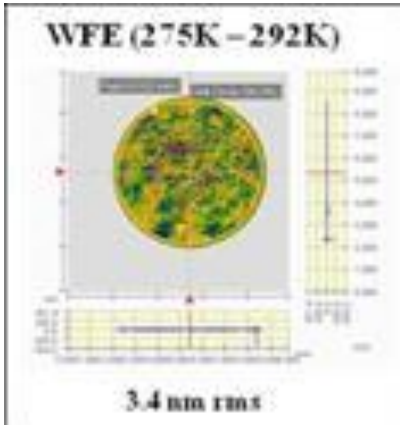
Mid/High Spatial Frequency Error

- Harris polished 43 cm deep-core mirror to a zero-gravity figure of 5.5 nm rms using ion-beam figuring to eliminate quilting.



- MSFC tested 43 cm mirror from 250 to 300K. Its thermal deformation was insignificant (smaller than 4 nm rms ability to measure the shape change)



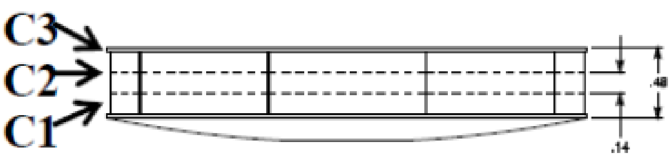


Large Stable Mirror Substrates

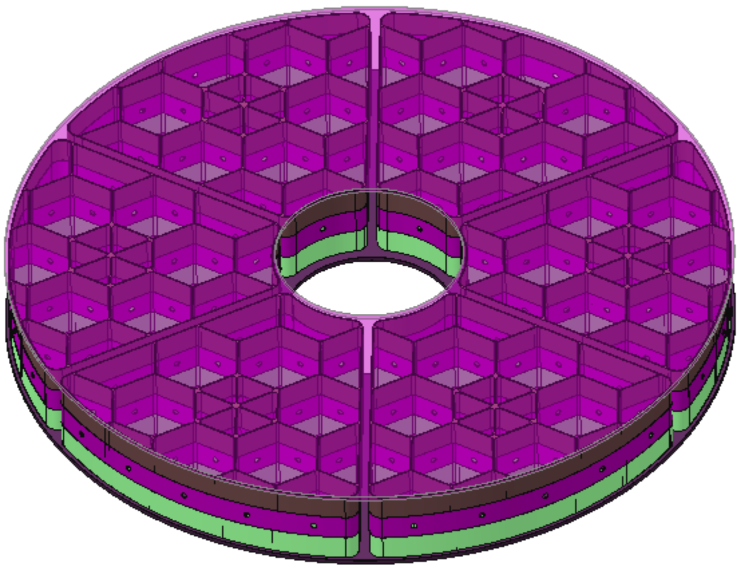
Phase 2 demonstrated lateral scaling of the stacked core process by making a 1.5 m subscale of a 4-m mirror.

Designed 4-m x 500 mm on-axis mirror then scale down to 1.5 m x 185 mm.

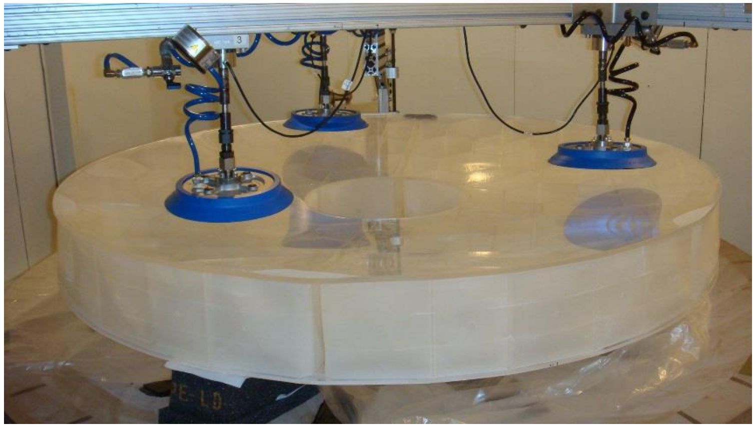
- (2) ULE® face plates
- (3) ULE® glass boules

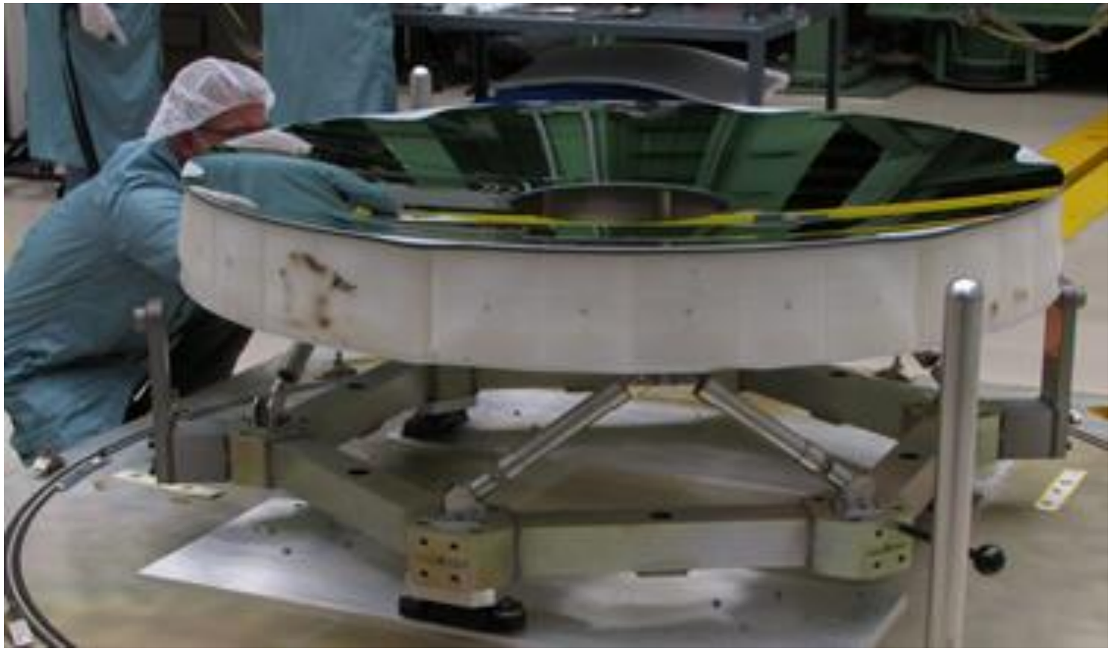


4m PM Conceptual Layout



1.5-m x 185 mm 450 Hz ULE® Mirror

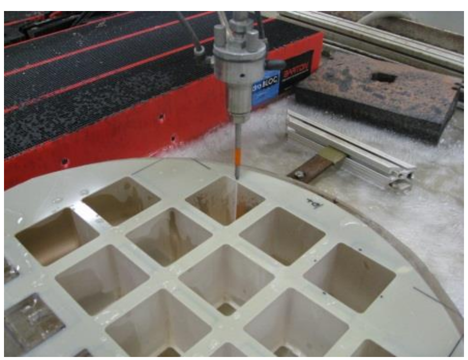




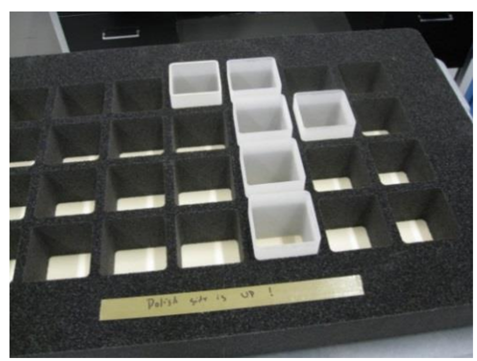
Photo's courtesy of Harris Corporation

Strength Testing

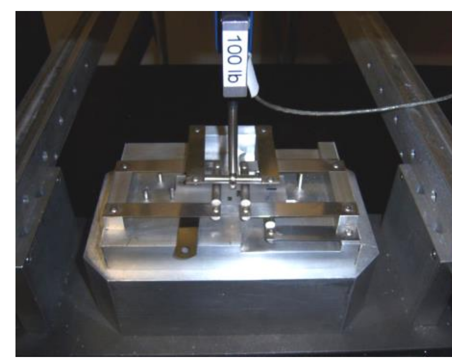
- AMTD-1: Harris strength tested the core to core LTF bond strength on 12 Modulus of Rupture (MOR) test articles.
  - Weibull 99% survival value was 15% above conservative design allowable. Data ranged from 30% to 200% above design allowable.
- AMTD-2: A-Basis test of core rib to core rib LTF bond strength.
  - 60+ MOR Samples: 30+ samples aligned; 30+ core misaligned
  - A-basis Weibull 99% confidence strength allowable for 49 samples is 17.5MPa; ~50% higher than the strength of core-to-plate LTF bonds.



MOR Boxes in Abrasive Water Jet (AWJ)



post AWJ, pre-LTF assembly

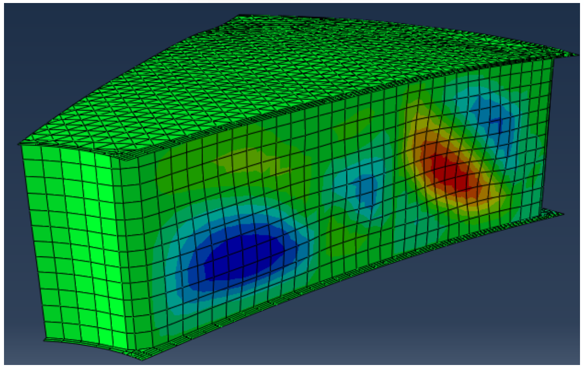


MOR sample in Test Fixture

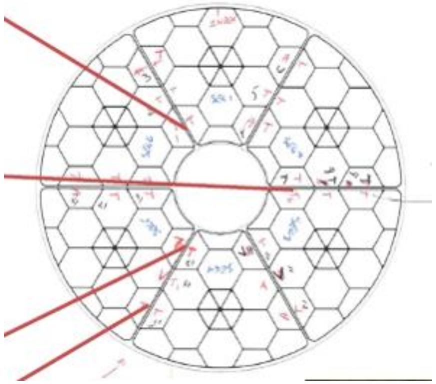
Visco-Elastic Behavior

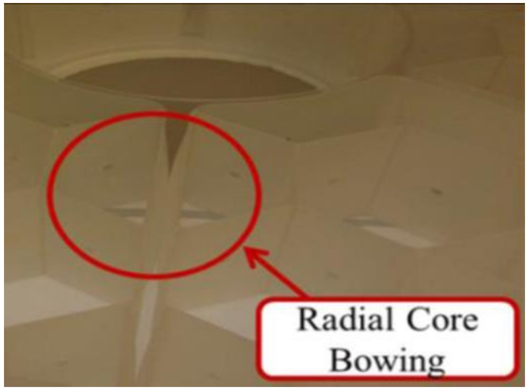
Non-linear visco-elastic modeling predicted Wall Bowing.

Mirror was designed to accommodate predicted bowing.



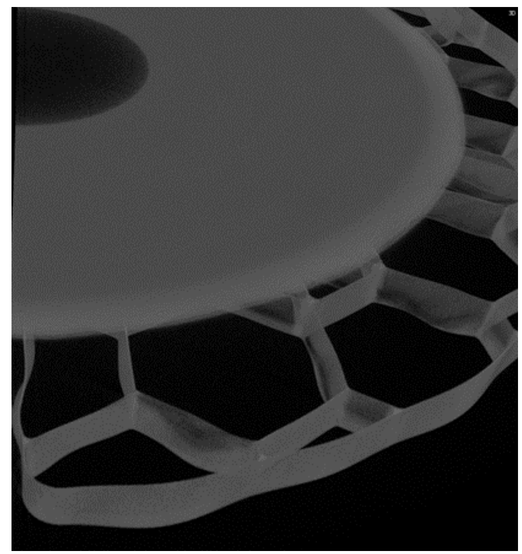
Unfortunately, while the core walls never touched, they did get within <0.25 mm at four locations.





Visco-Elastic Behavior

X-Ray Computed Tomography used to quantify internal mirror structure and correlate with visco-elastic model to create ‘as-built’ STOP model.



Lessons Learn have been documented.

1.5-m ULE® Mirror Status

Next is Thermal Performance characterization testing.

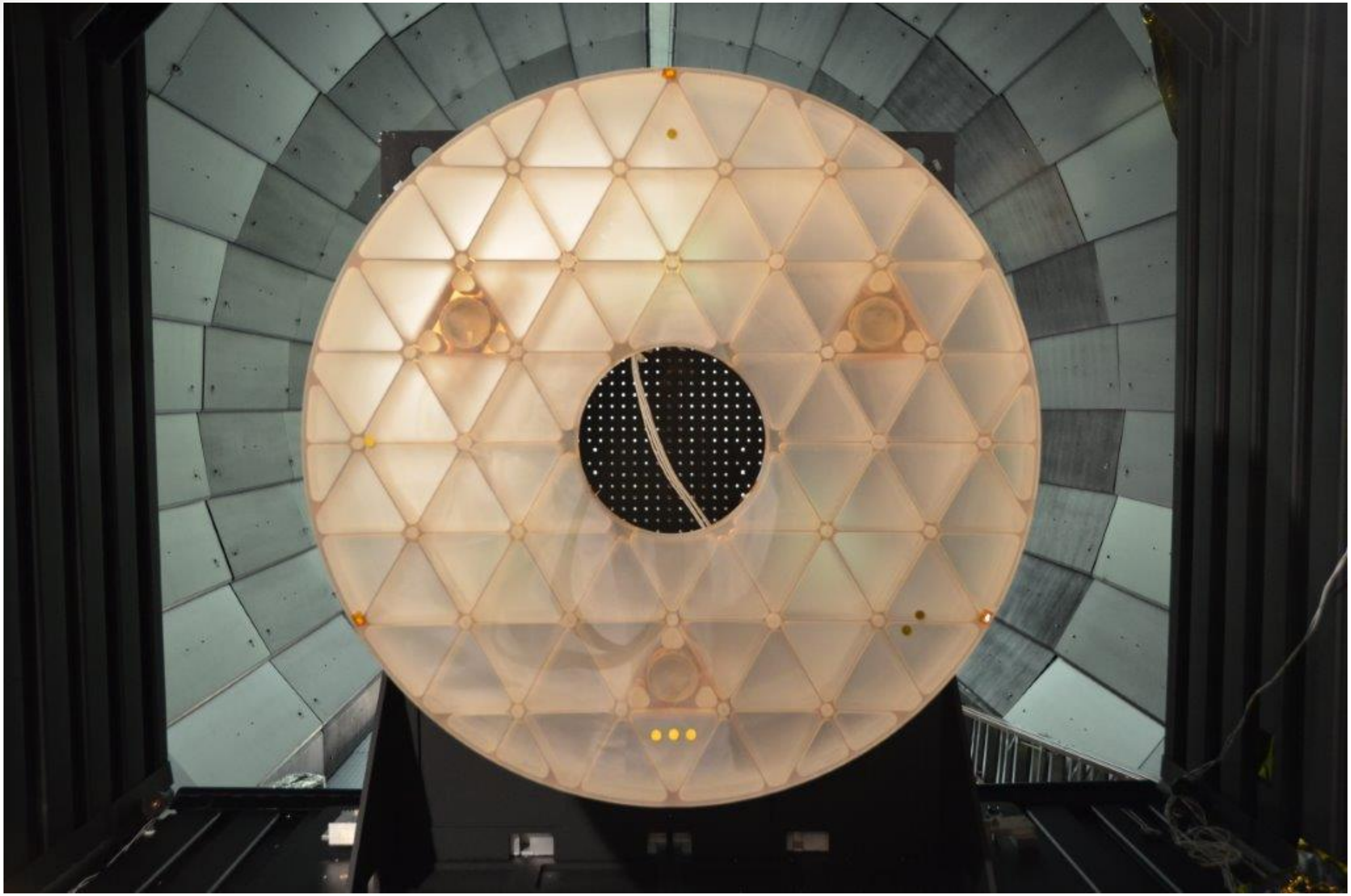
Given the importance of mid-spatial frequency errors (both static and dynamic) in producing the ‘dark-hole’, AMTD will quantify:

- Thermal induced quilting.
- CTE variation induced Surface Figure Error
- Surface Thermal Stability

AMTD did this for the Schott 1.2m Extreme-Lightweight Zerodur Mirror (ELZM).

AMTD also predicted and quantified ELZM static and dynamic mechanical performance (gravity sag and first mode frequency).

Schott ELZM Model Correlation Tests

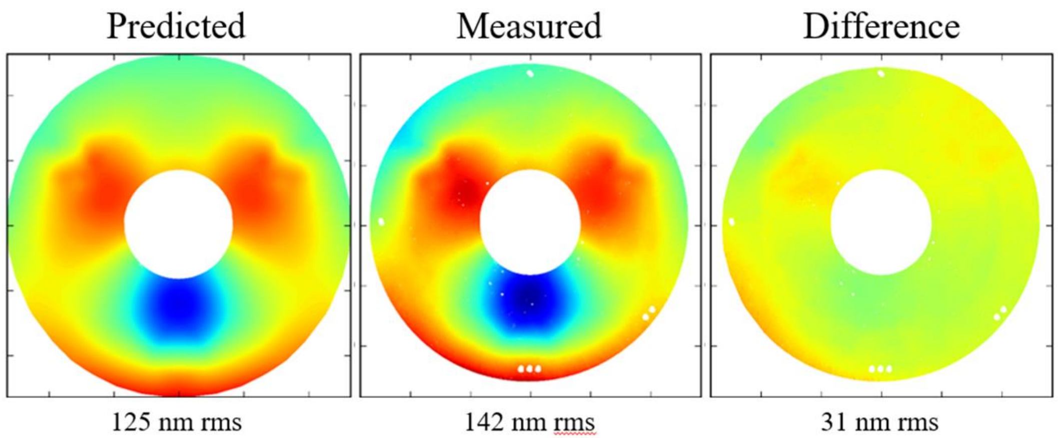


Diameter: 1.2m ROC: 3.1m Mass: 45kg; 88% lightweighted

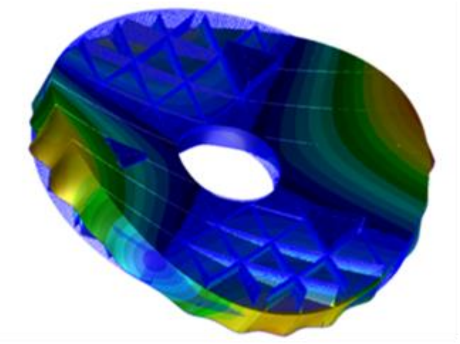
Mechanical Model Validation

Mechanical Model was validated by quantifying:

- Gravity Sag, i.e. mirror's response to static load



- First Mode Frequency, i.e. mirror's response to dynamic load

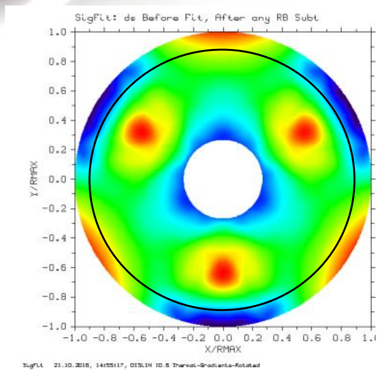


With foam blocks
F1 = 206.89 Hz

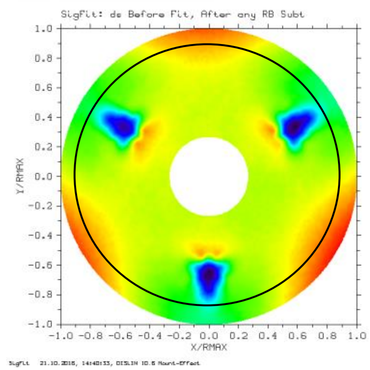
Measured: 196.07 Hz

Thermal Model Validation for 294K to 250K

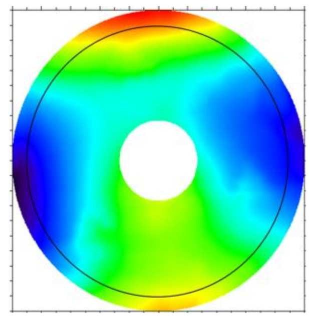
A Prior Analysis



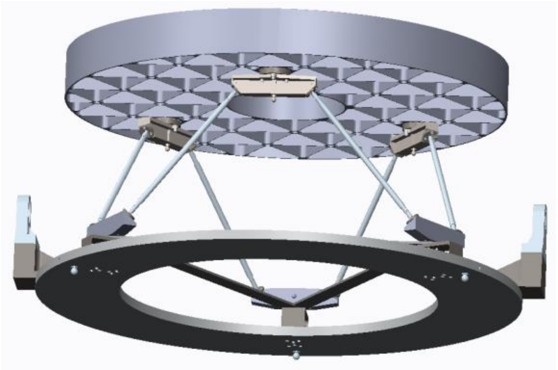
Thermal Gradients
(1.28 nm RMS)



Mount Effects
(0.81 nm RMS)

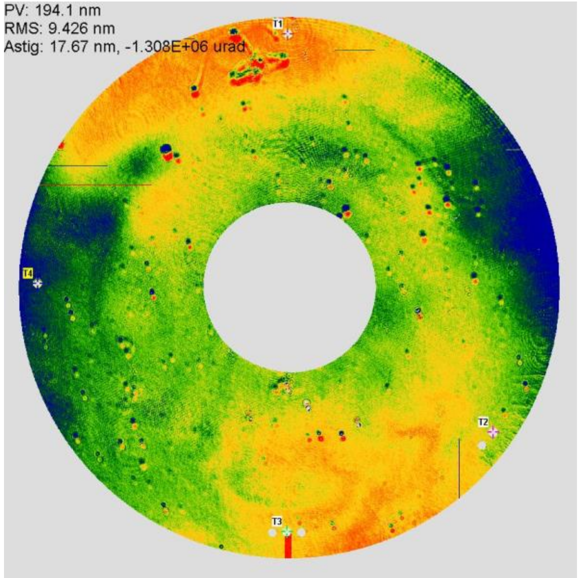


Inhomogeneity*
(9.55 nm RMS)



* Random CTE map was generated with Schott specified 5 ppb/K PV homogeneity.

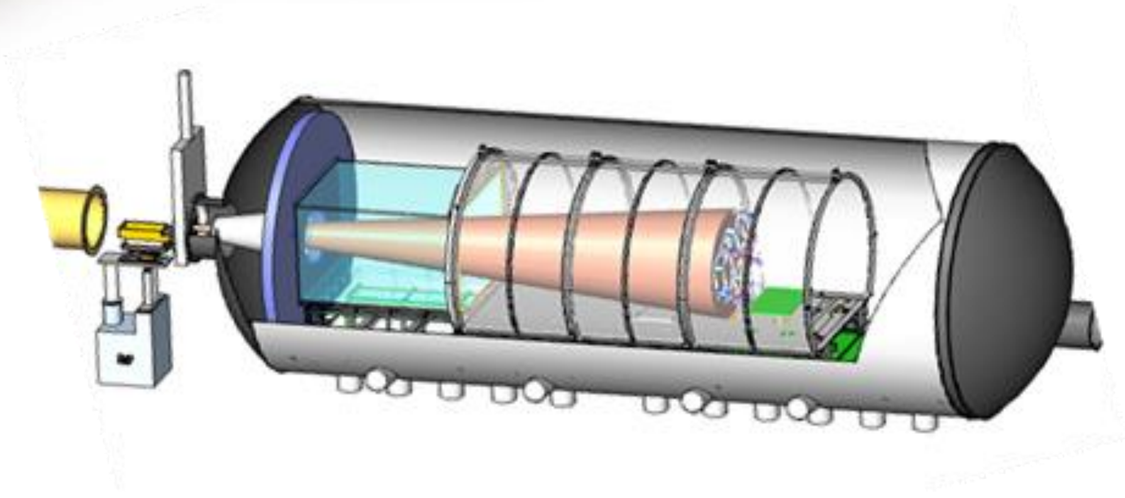
Test Results

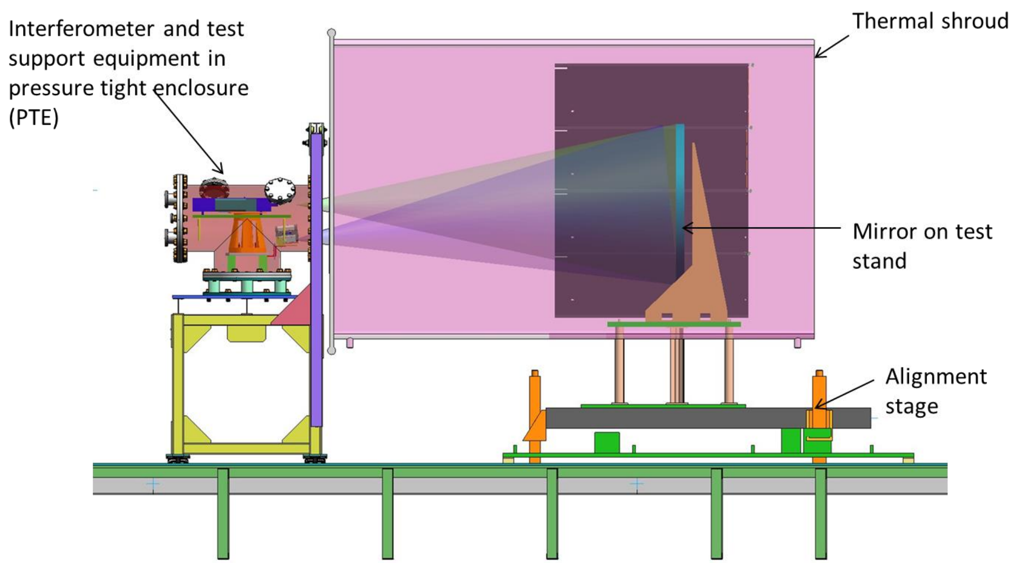


Measured SFE (9.4 nm RMS)

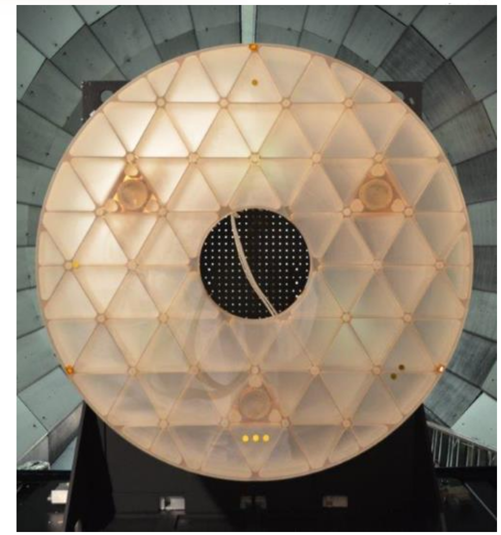
- **CTE drives thermal performance.**
- **Model accuracy depends on CTE knowledge.**

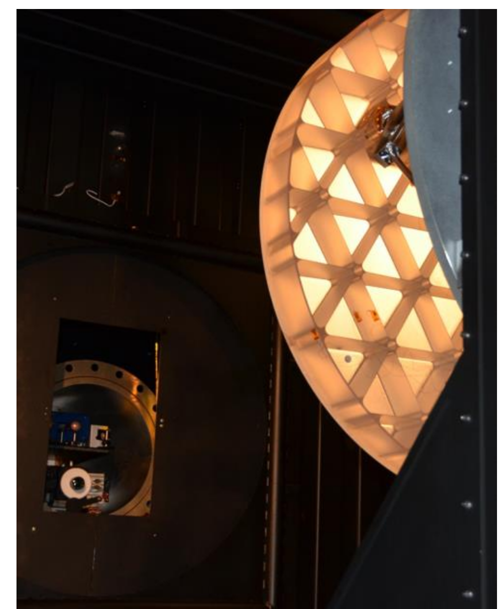
MSFC Thermal-Optical Test Capabity





AMTD-2 test configuration with PTE





Test Measured Data at 250K

ΔT~0.8K

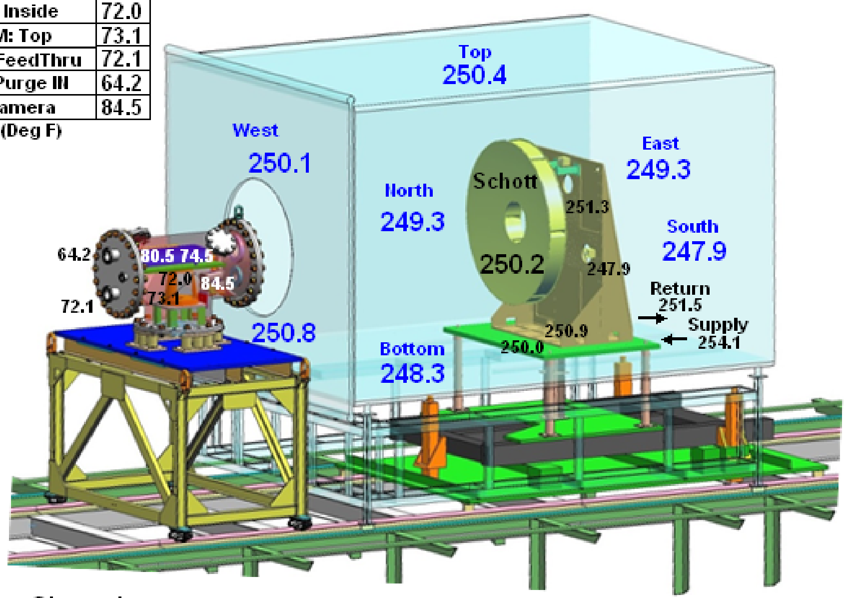
09/16/16 08:10:57

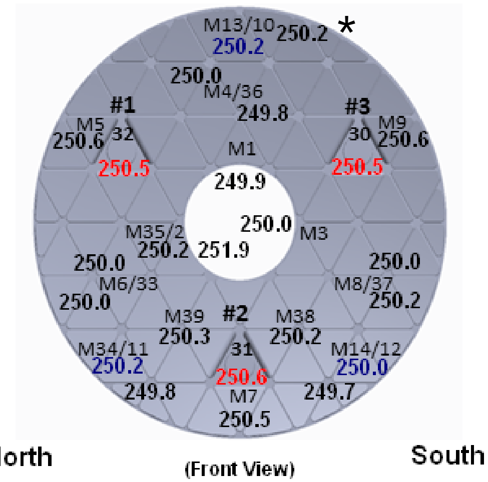
AMTD2 / Schott Cryo Test

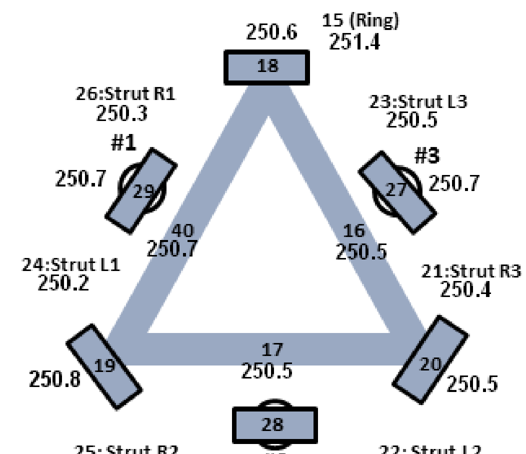
PTE

PhaseCam East	74.5
PhaseCam West	80.5
PTE: Inside	72.0
ADM: Top	73.1
Cable FeedThru	72.1
PTE: Purge IN	64.2
IR Camera	84.5

(Deg F)







Shroud

Top	250.4
North	249.3
South	247.9
Bottom	248.3
West Top	250.1
West Bottom	250.8
East	249.3

(Kelvin)

	Shroud			Schott	
Average	249.4	K	Average	250.2	K
Rate	-0.1	K/HR	Rate	-0.1	K/HR
Max	250.8	K	Max	251.9	K
Min	247.9	K	Min	249.7	K
Grad	3.0	K	Grad	2.2	K

M1- Top Hole	249.9
M2 - North Hole	251.9
M3 - South Hole	250.0
M4 - 12:00	250.0
M5 - 10:00	250.6
M6 - 8:00	250.0
M7 - 6:00	250.5
M8 - 4:00	250.2
M9 - 2:00	250.3
M10- Top Edge	250.2
M11 - 8:00 Edge	249.8
M12 - 4:00 Edge	249.7
M13 - Top Front	250.2
M14 - 4:00 Front	250.0
M33 - 8:00 (w/M6)	250.0
M34 - 8:00 (w/M11)	250.2
M35 - 8:00 (w/M2)	250.2
M36 - 12:00 (w/M4)	249.8
M37 - 4:00 (w/M8)	250.0
M38 - 5:00	250.2
M39 - 7:00	250.3
30 - South Pad	250.5
31 - Bottom Pad	250.6
32 - North Pad	250.5
15 - 12:00 Ring	251.4
16 - Delta_3	250.5
17 - Delta_2	250.5
18 - Top Bracket	250.6
19 - South Bracket	250.8
20 - North Bracket	250.5
21 - Strut R3	250.4
22 - Strut L2	250.4
23 - Strut L3	250.5
24 - Strut L1	250.2
25 - Strut R2	250.6
26 - Strut R1	250.3
27 - South Mount	250.7
28 - Bottom Mount	250.7
29 - North Mount	250.7
[illegible] - Delta_[illegible]	[illegible]

(Kelvin)

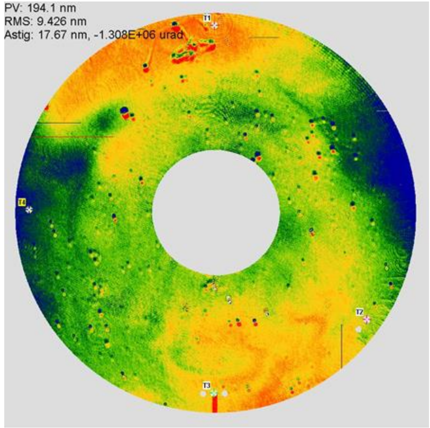
*Likely anomalous measurement ignored

Quilting

While the cryo-deformation phase maps show negligible quilting associated with the mechanical structure of the mirror substrate, there is ‘fringe print through’.

The ‘fringe print-through’ is caused by two factors:

- Mirror surface figure is ~400 nm PV
  - Gravity Sag ~ 300 nm Astigmatism PV
  - Zero-G Figure ~ 115 nm PV
- The PhaseCAM uses a 4-bucket algorithm.

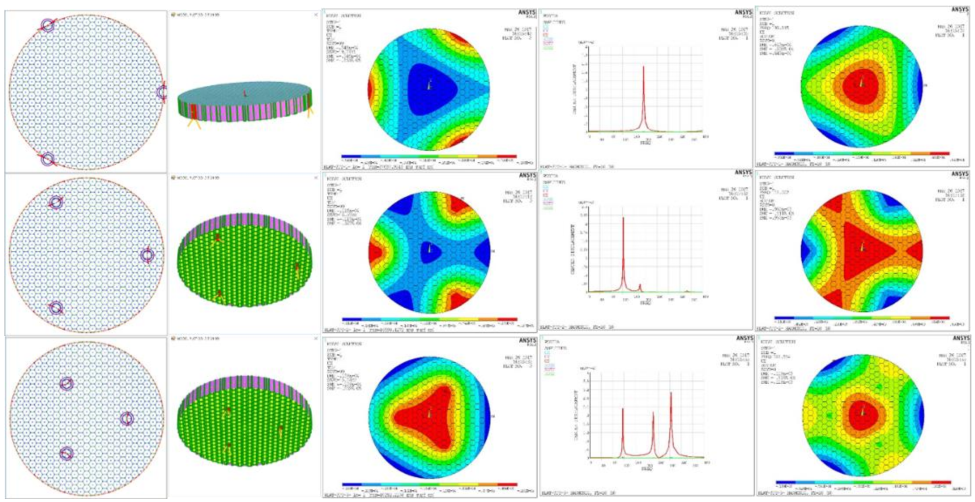


Measured SFE (9.4 nm RMS)

A known feature of the 4-bucket algorithm is that if the phase-shift is not exact, there is a ‘ghost’ pattern in the phase map with spatial frequency 2X that of the fringes.

Design/Analysis Modeling Tools

Arnold Mirror Modeler is designing and analyzing performance of candidate 4-m mirror assemblies for HabEx.



Coronagraph Contrast Leakage Model is informing HabEx Telescope alignment stability tolerances.

Table 1: PV Aberration Amplitude Tolerance for Contrast Leakage over an annular ROI from 1.5 to 2.5 λ/D

Aberration (Random)	WFE (pm) for 1×10^{-10} of Photometric Noise	WFE (pm) for 5×10^{-11} of Systematic Noise
Tip/Tilt	9,600	35,000
Seidel Power	1,100	22,000
Zernike Astigmatism	6,800	49,000
Zernike Trefoil	6,800	44,000
Zernike Hexafoil	9,600	78,000
Seidel Spherical	300	11,000
Seidel Coma	6,800	840

Conclusions

- AMTD uses science-driven systems engineering to derive performance specifications from science requirements then define & execute a long-term strategy to mature technologies to enable future large aperture space telescopes.
- Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.
- AMTD Phase 2:
  - Fabricate ⅓-scale model of a 4-m x 400-mm class ~150 Hz ULE® mirror (1.5-m x 185-mm 450 Hz).
  - Characterize optical performance of two candidate lightweight primary mirrors from 250K to ambient: 1.2-m ELZM and 1.5-m ULE.
  - Correlate Integrated Modeling Tools
- Lessons Learned from the 1.5m ULE mirror have been documented.

Technical Accomplishments

AMTD enables & enhances future missions such as **HabEx and LUVOIR**

- Developing process to fabricate 4-m class (& larger) mirrors at lower areal density, lower areal cost & lower risk using stacked core technology.
  - Phase 1: demonstrated ability to make 40-cm thick mirror
  - Phase 2: demonstrating ability to laterally scale to 1.5 meters
- Lessons Learned for future substrate fabrication technology
- Validate Performance Models of Schott Mirror by Test
  - Thermal Characterization (including use of infrared camera)
  - Modal Characterization
- Coronagraph Contrast Leakage vs Telescope Stability Study influencing
  - LUVOIR and HabEx
  - ExEP Coronagraph Performance with Segmented Aperture Study
- Modeling & Analysis Tools are being used on HabEx and PTC
  - Arnold Mirror Modeler enhancement and trade studies transitioned to HabEx
  - Thermal MTF analysis transitioned to Predictive Thermal Control SAT